ABSTRACT
In support of NASA ARMD's code validation project, we have made significant progress by providing the first quantitative single-shot multi-scalar data from a turbulent elevated-pressure (5 atm), swirl-stabilized, lean direct injection (LDI) type research burner operating on CH4-air using a spatially-resolved pulsed-laser spontaneous Raman diagnostic technique. The Raman diagnostics apparatus and data analysis that we present here were developed over the past 6 years at Glenn Research Center. From the Raman scattering data, we produce spatially-mapped probability density functions (PDF's) of the instantaneous temperature, determined using a newly developed low-resolution effective rotational bandwidth (ERB) technique. The measured 3-scalar (triplet) correlations, between temperature, CH4, and O2 concentrations, as well as their PDF's, also provide a high-level of detail into the nature and extent of the turbulent mixing process and its impact on chemical reactions in a realistic gas turbine injector flame at elevated pressures. The multi-scalar triplet data set presented here provides a good validation case for CFD combustion codes to simulate by providing both average and statistical values for the 3 measured scalars.

Single-Shot Scalar-Triplet Measurements in High-Pressure Swirl-Stabilized Flames for Combustion Code Validation

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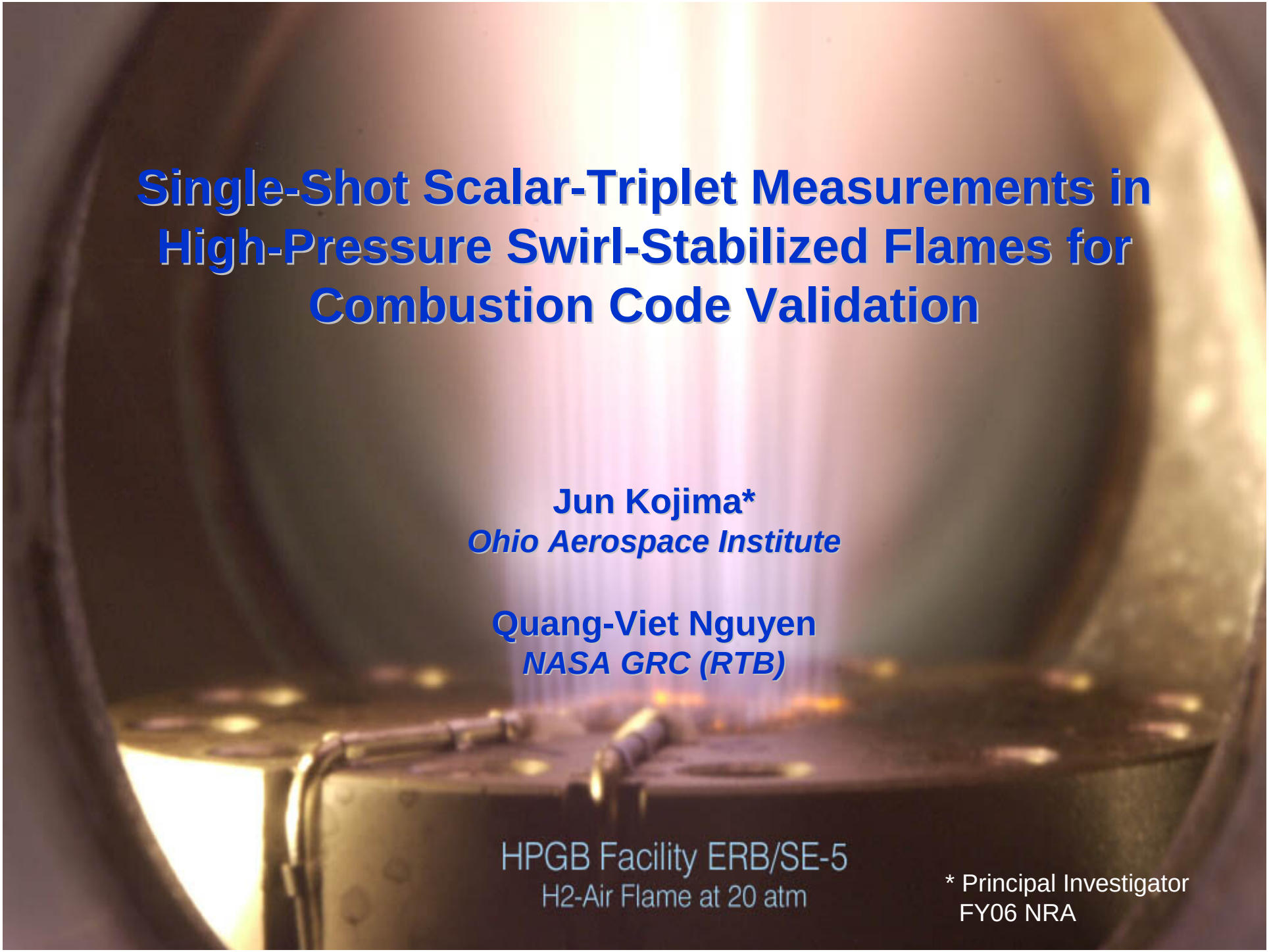


* Principal Investigator
FY06 NRA

Overview

Goal: Provide critical chemical and physical data in turbulent combustion at realistic subsonic/supersonic cruise condition for ***validating predictive low-emissions combustor codes***

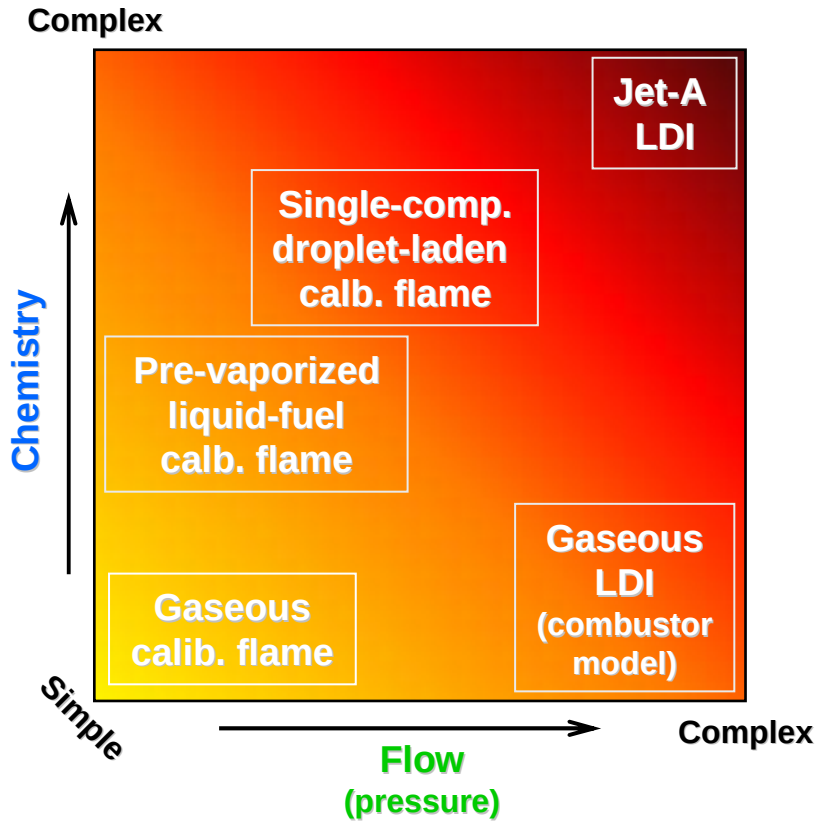
Challenges: Successful accurate multiscalar measurements (temperature, major species mole fractions, mixture fraction, velocity) in optically-harsh droplet-laden flows at ***high pressures***.

Strategy (tasks):

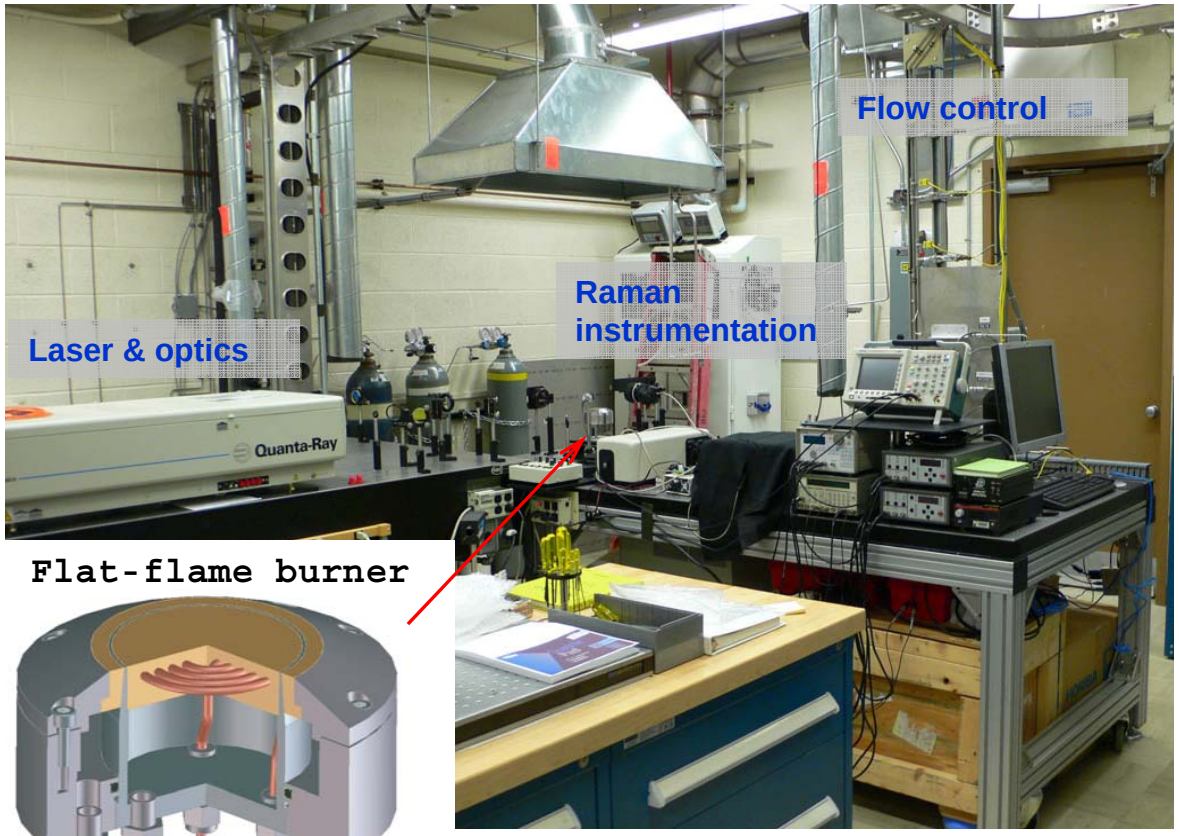
✓ Develop a quantitative time-resolved ***laser Raman diagnostics***

✓ A series of experiments of increasing flow complexity: (i) Calibration burner (e.g., flat-flame burner), (ii) Realistic concept burners (swirl-stabilized burner) at elevated pressures up to 10~30 atm

✓ Address the effects of chemical complexity: H_2, CH_4, single-component liquid (e.g., hexane, iso-octane, n-heptane), jet-A fuel



Atmospheric Pressure Combustion Diagnostics Facility

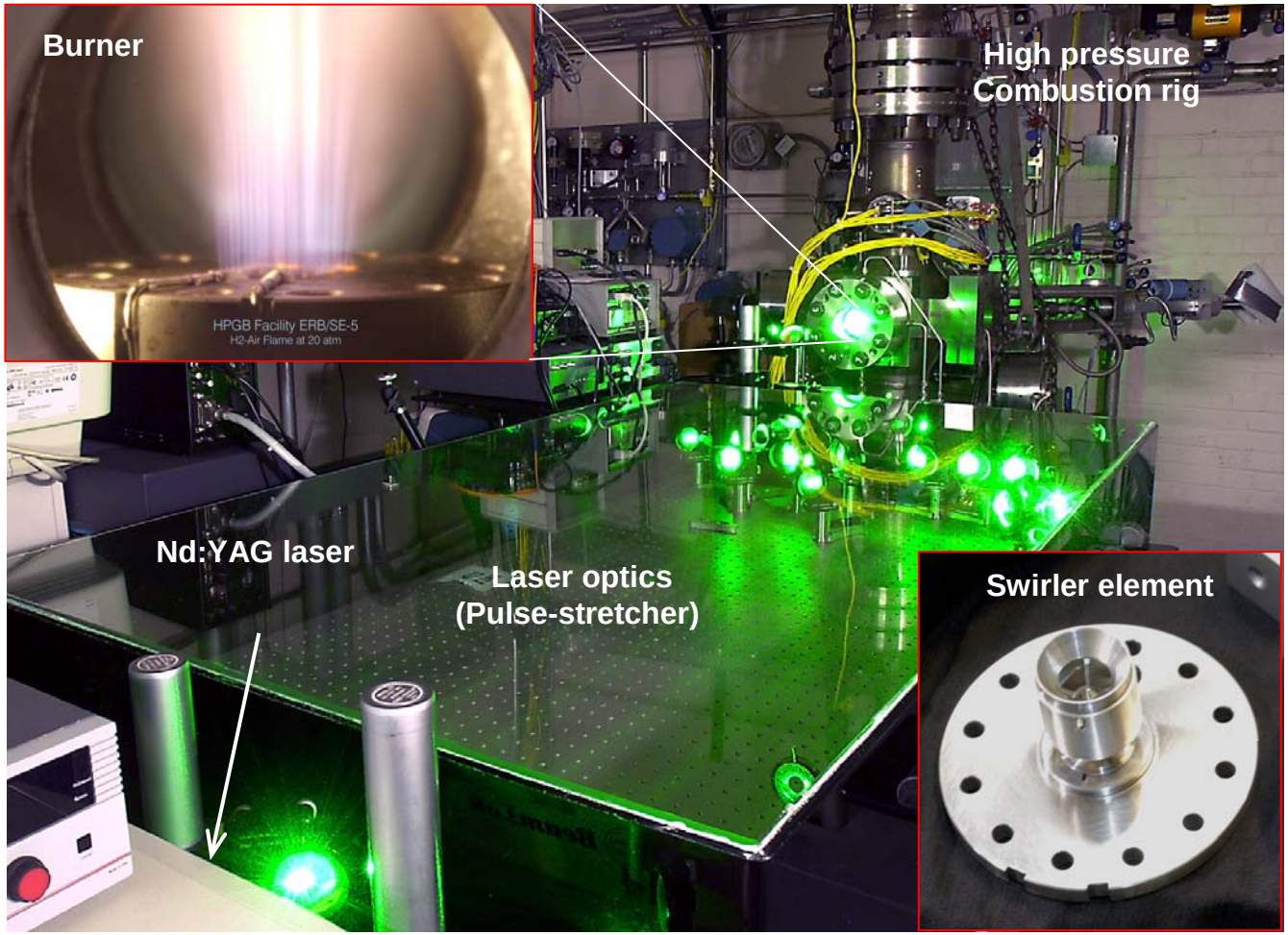


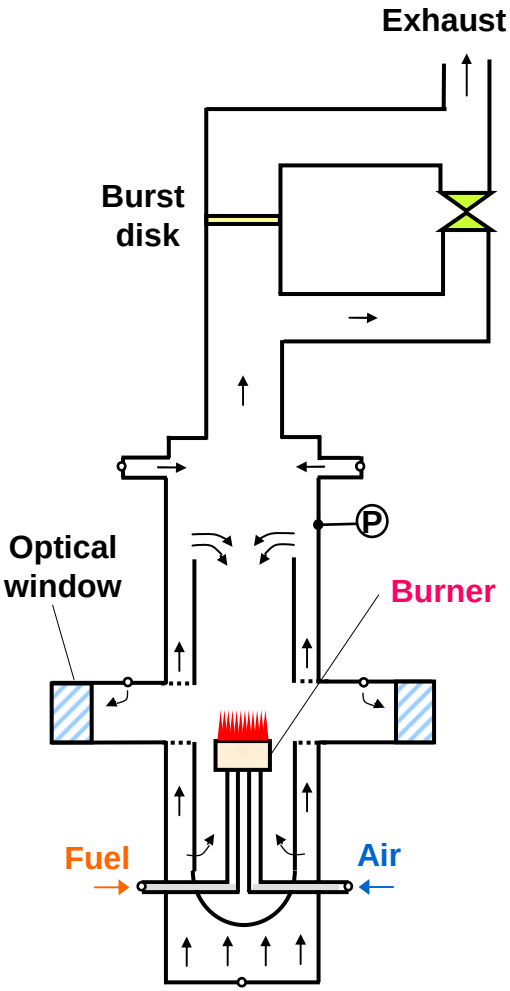
Flat-flame burner

Fuel/air mixture
(gas, or pre-vaporized liquid fuel)

- Temperature and species reference
- Diagnostics calibration
- Gaseous fuels
- Pre-vaporized single-component liquid fuel (electronically controlled fuel vaporizer and heating system)
- Support visible and UV laser Raman systems
- Study on optical characteristics of sooting flames and liquid fuel combustion chemistry
- Support the Aeronautics milestones to mitigate risks due to PSO holding up high-pressure experiments

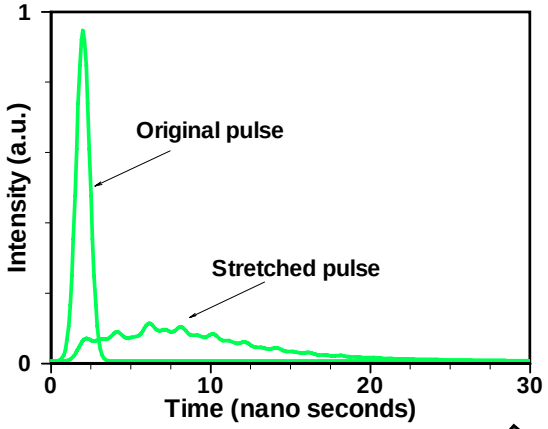
High Pressure Burner Facility (SE-5)





- ✓ Remotely controlled with auto process controller
- ✓ Pressure up to 30 atm (currently 10 atm requested for safety permit)
- ✓ Versatile for burner platform (calibration burner, turbulent jet, LDI)
- ✓ Optical access (4 ports)
- ✓ Gaseous and liquid fuel capacity
- ✓ Air pre-heater installed (up to 1200F)

Raman Scattering Diagnostic System



Nd:YAG Laser (800 mJ/pulse)

Beamsplitters

Laser Pulse-Stretcher
(passive multiple ring-cavity)
*Patent pending

Mirrors

High-Pressure Rig

Burner

Folding
Prism

Optical Fibers

Electro-mechanical
high-speed shutter
*2007 R&D 100 Award
• 10's µs gate width

Holographic
spectrograph (f/1.8)

Laser line
filter

PC

CCD
• 1340 x 100 pixels
• 90% Q.E.
• 16 bit A/D

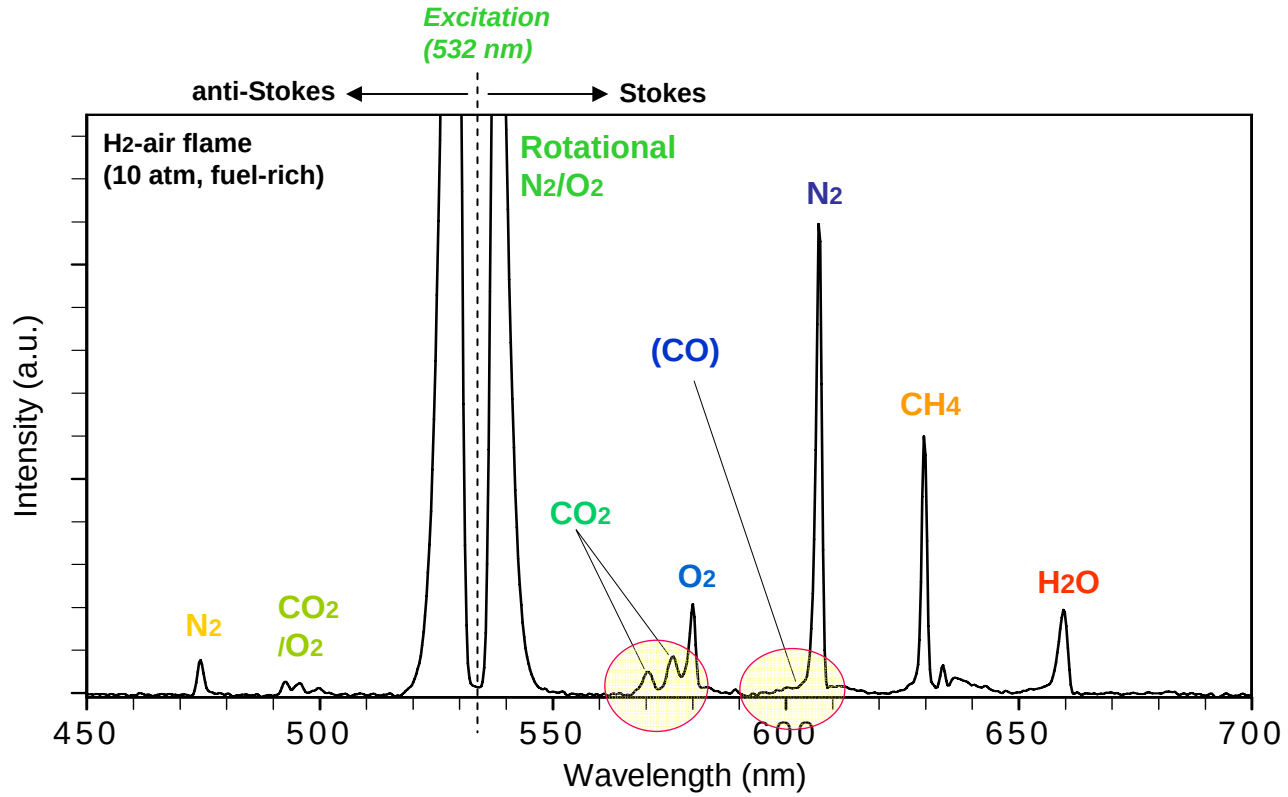
Raman Spectra Observed in Combustion

Advantage

- Raman scattering –simultaneous multiple species concentration and temperature
- Time-average (mean) or Single-shot (instantaneous; rms)
- Quantitative

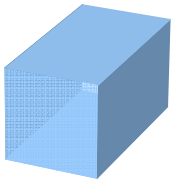
Challenge

- Spectral interference (**'Cross-talk'**)

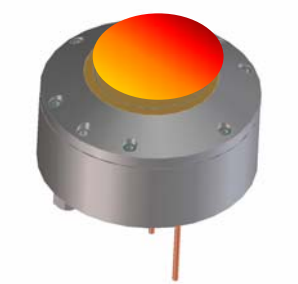


Raman Calibration Experiments & Simulation

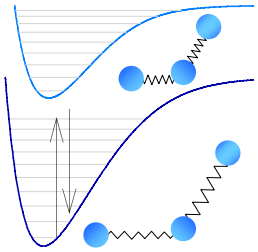
Platform



Static cell



Calib. burner



Raman spectrum simulation

+

Fuel
(lean ~ rich)

H_2
H_2-CO
CH_4
Single-component liquid (pre-vaporized)
Single-component liquid
Multi-component (jet-A)

Air

+

Raman Instrumentation

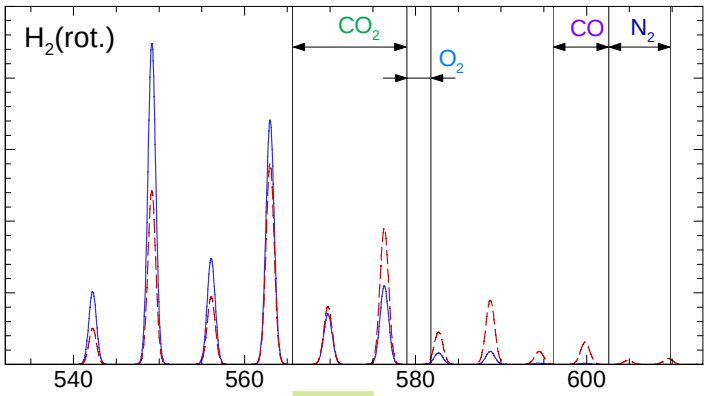
Pump lasers: 532/355/266 nm
Thermometry: Vib. / Rot.
Polarization property

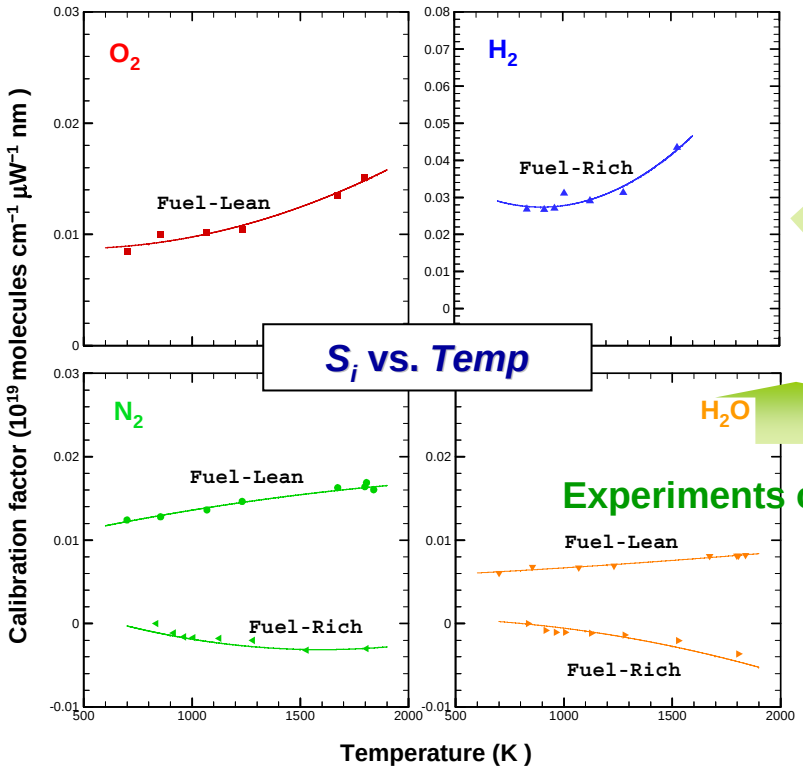
Matrix elements, $k_{i,j}(T)$
(Cross-talks)

Major species (H_2, O_2, N_2, CO, CO_2, H_2O, HC's)
H_2 ▶ CO
H_2 ▶ CO_2
H_2 ▶ H_2O
N_2 ▶ CO
O_2 ▶ CO_2
CO_2 ▶ N_2
C_2* ▶ N_2, CO, HC's
PAH ▶ Broadband background

Determine the 'Cross-talk' Calibration Matrix

Raman Spectra Library





S_i vs. *Temp*

Experiments or Simulations

Calibration matrix

High temp.

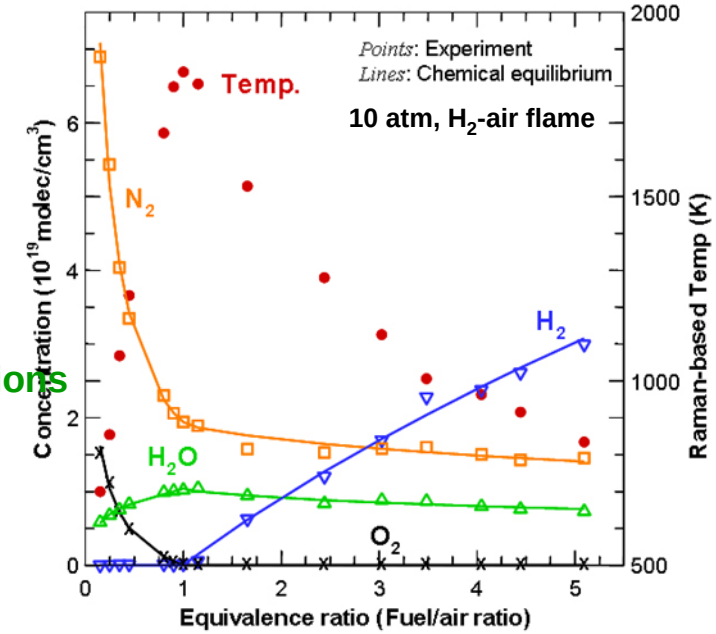
Low temp.

Mole frac.

$$N_i = (1/E_{laser})\, k_{i,j}(T)\, S_i$$

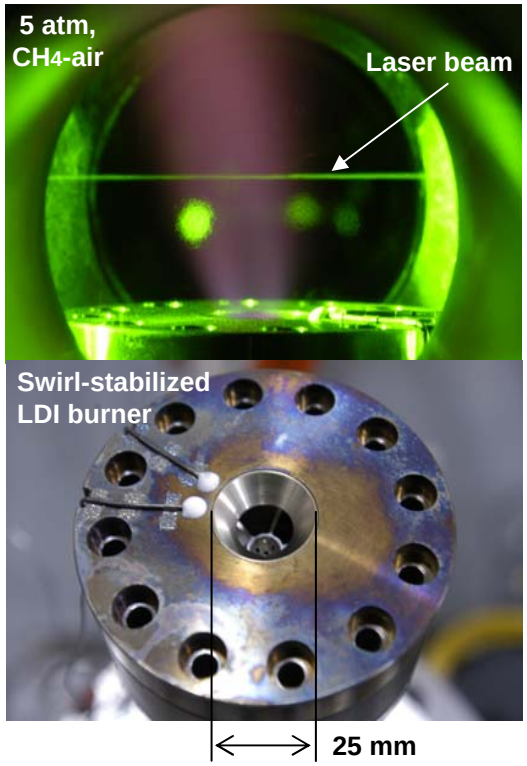
Raman signal

Calibrated Results

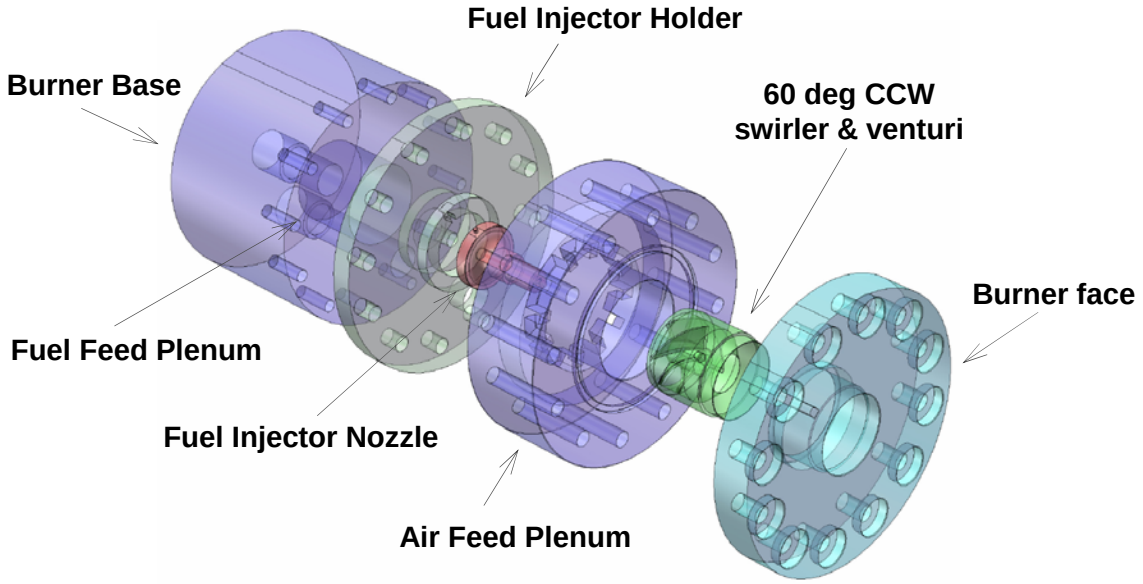


NASA Lean Direct Injection (LDI) Swirl-Stabilized Research Burner
— Preliminary Test —

Photos of LDI flame and burner face



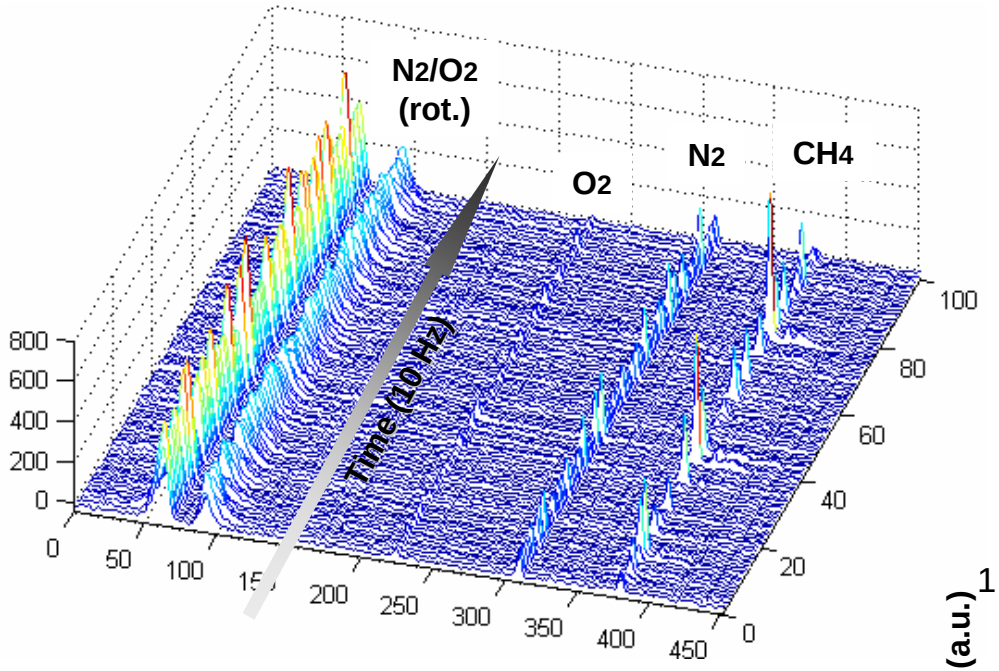
Single Gaseous LDI Injector Design (Solid model for CFD)



- Swirl-stabilized direct fuel injection design (gaseous)
- Integrated with existing high-pressure rig
- 6 jets (0.8 mm in dia.) angled at 45 deg to burner axis
- Initial test on H_2 and CH_4 fuels with unheated air at 5 atm
- Collaborating with National Combustor Code (NCC)

Single-Shot (Time-Resolved) Raman Measurements

Time variation of single-shot Raman spectra in CH4-air LDI flame (5 atm, Phi = 0.5)

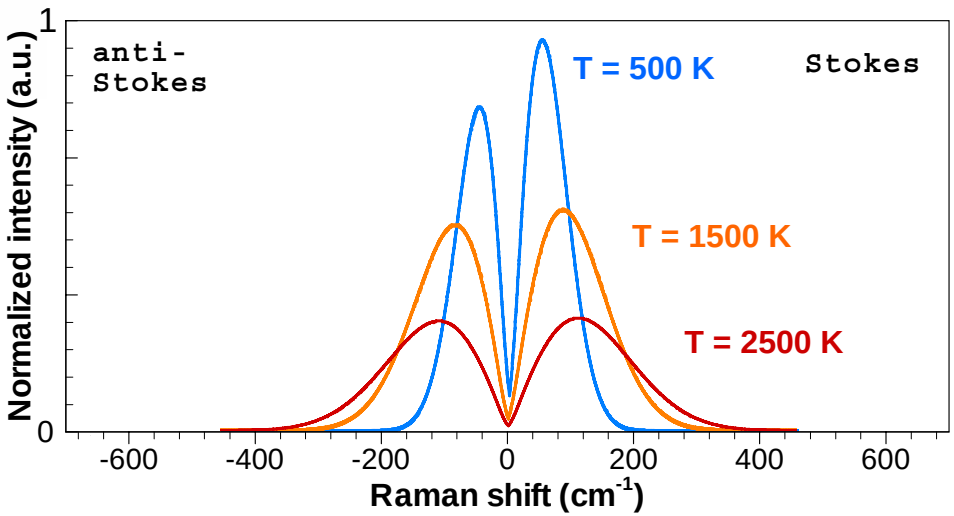


Raman shift (or wavelength)

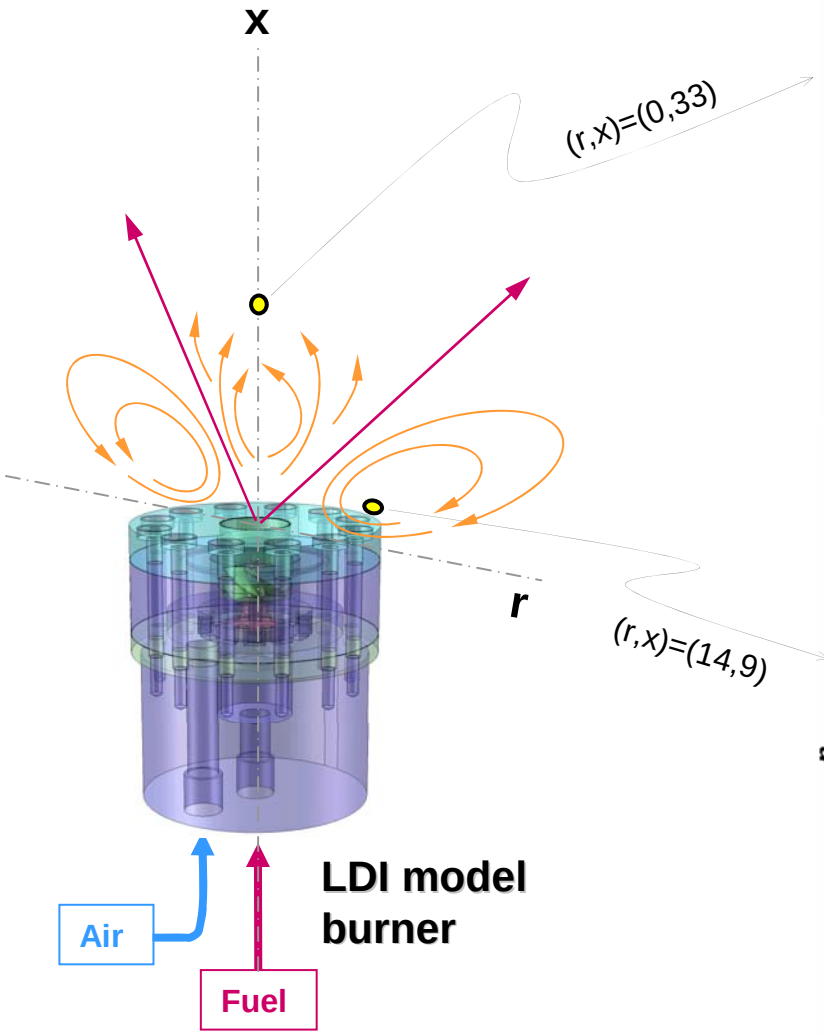
- One shot = One instance (space-time point)
- Single-shot Raman data shows “random” change due to turbulence
- Direct and simultaneous measurement of fuel/oxidizer concentrations and temperature (with data processing with calibration matrix)
- Developed new thermometry approach (rot. bandwidth) with high SNR

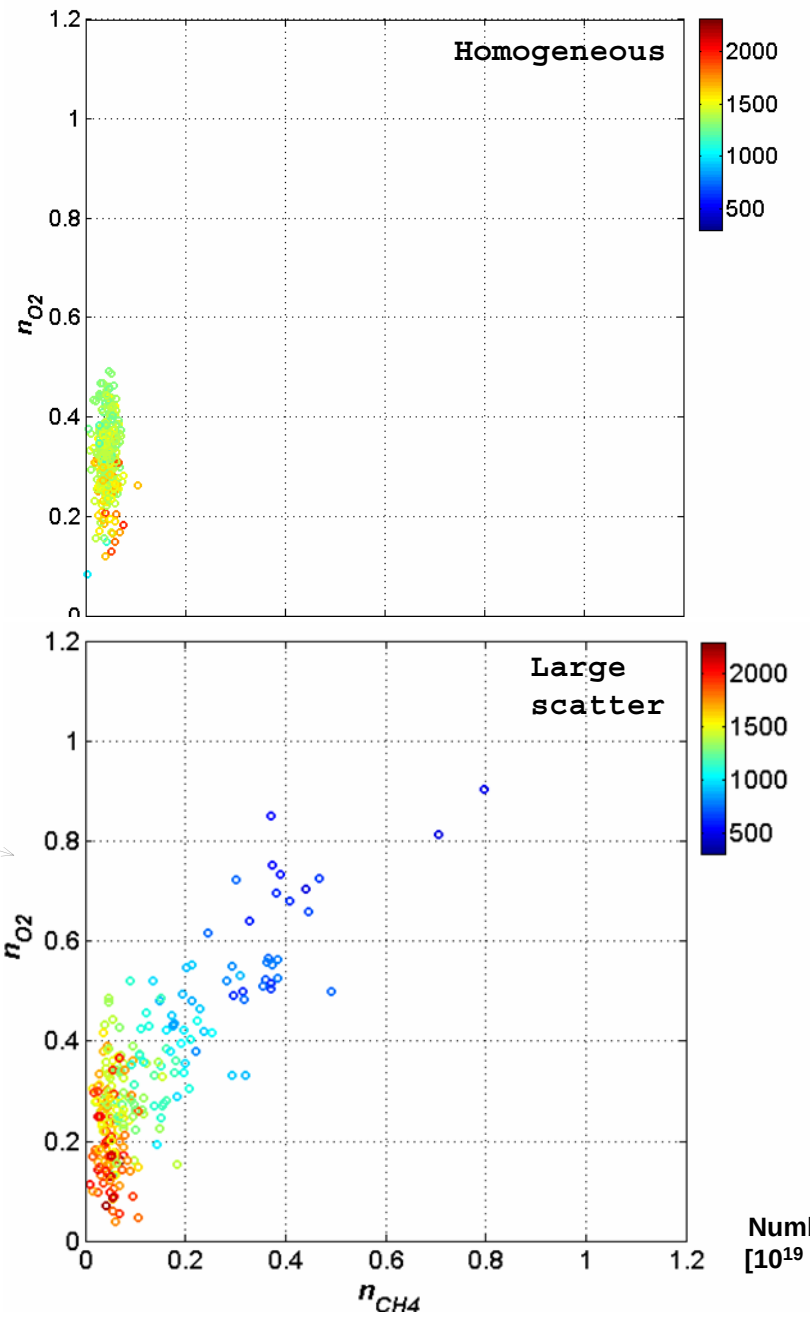
- Temperature from the rotational spectra has been measured with accuracy 7%
- Data permits statistical PDF’s of temperature and species
- Provides a signature for characterizing degree of mixing and reaction

Rotational N2 Raman band



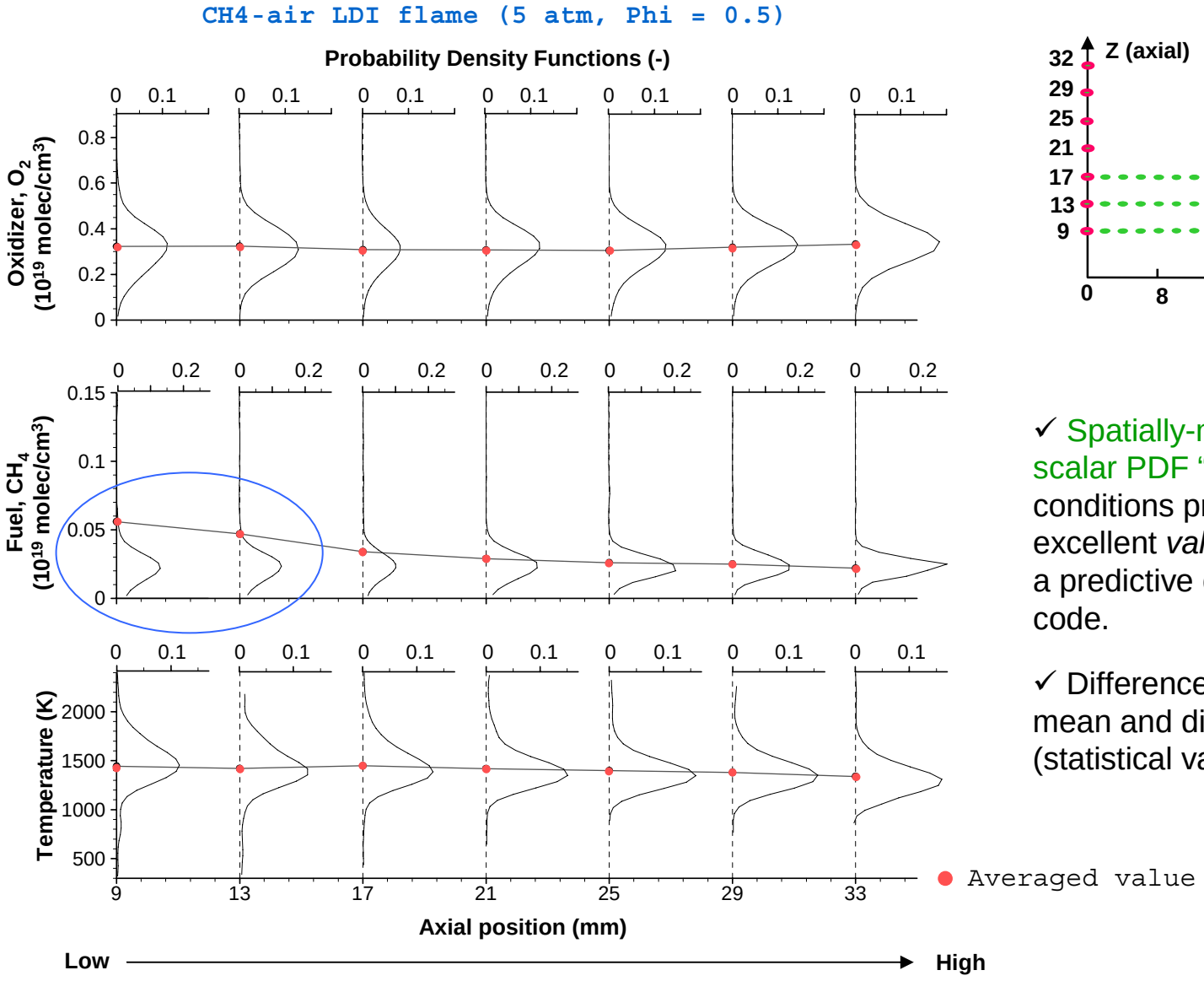
Processing the Single-Shot Data





Number density
[10^{19} molec/cm^3]

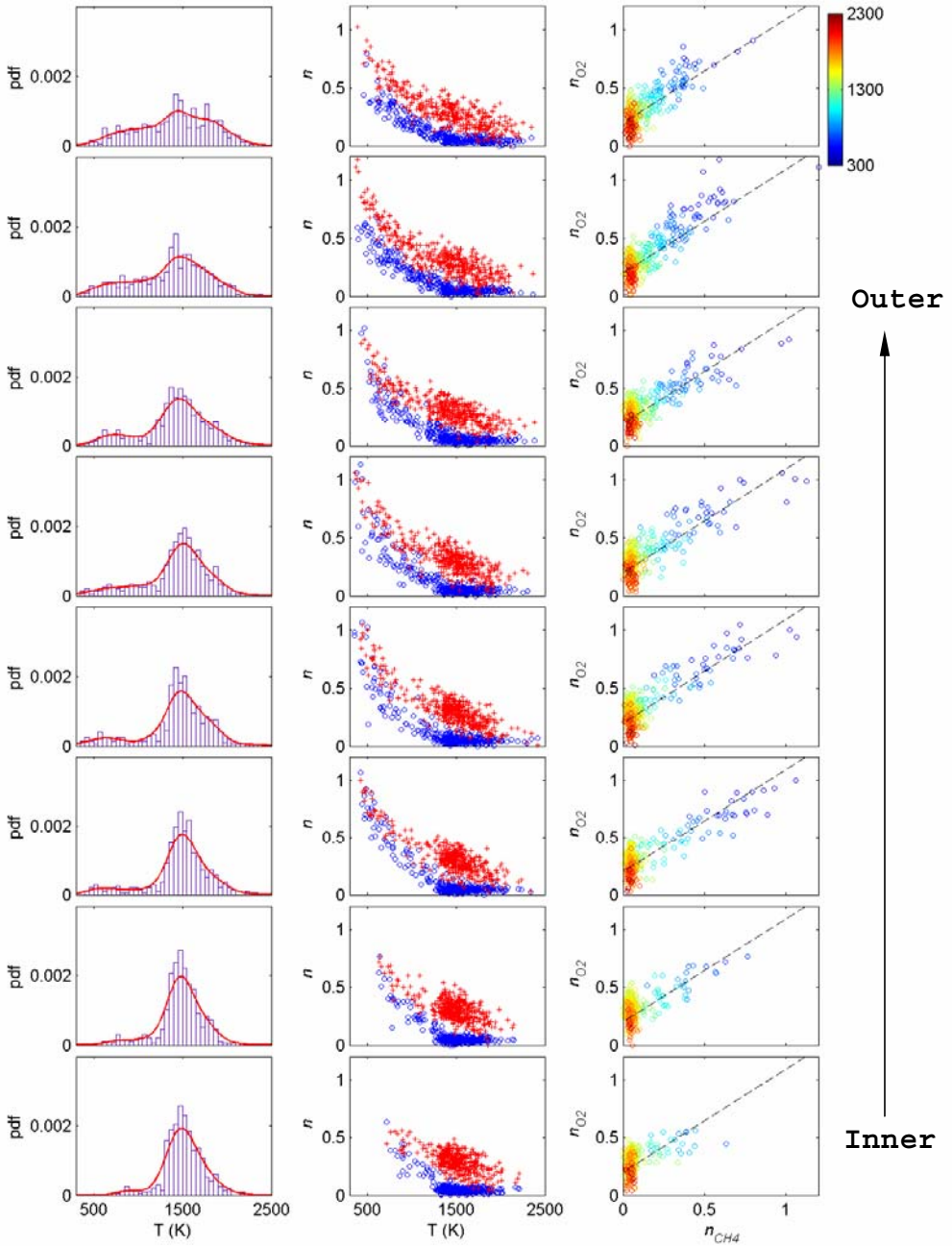
Probability Density Functions: PDF's
(Temperature, CH_4, and O_2)

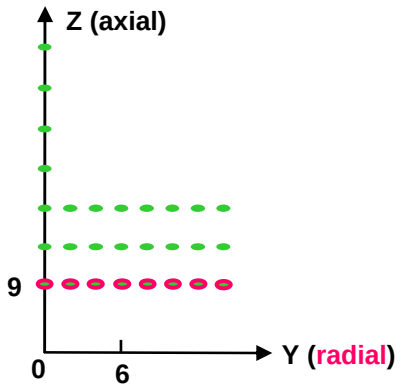


✓ Spatially-mapped multi-scalar PDF "library" in given conditions provides excellent *validation data* for a predictive combustion code.

✓ Difference between mean and distribution (statistical value)

Multiscalar Analysis in 5-atm CH_4-Air LDI Flame





'Production-mode' data

: Direct output from a MATLAB code

1. Temperture PDF's
2. Temp. vs species correlations (*red*: O_2; *blue*: CH_4)
3. Triplet correlations (temp-ox-fuel) (with a global Phi of 0.5 line)

Data interpretation

✓ Hot spots (high NOx)

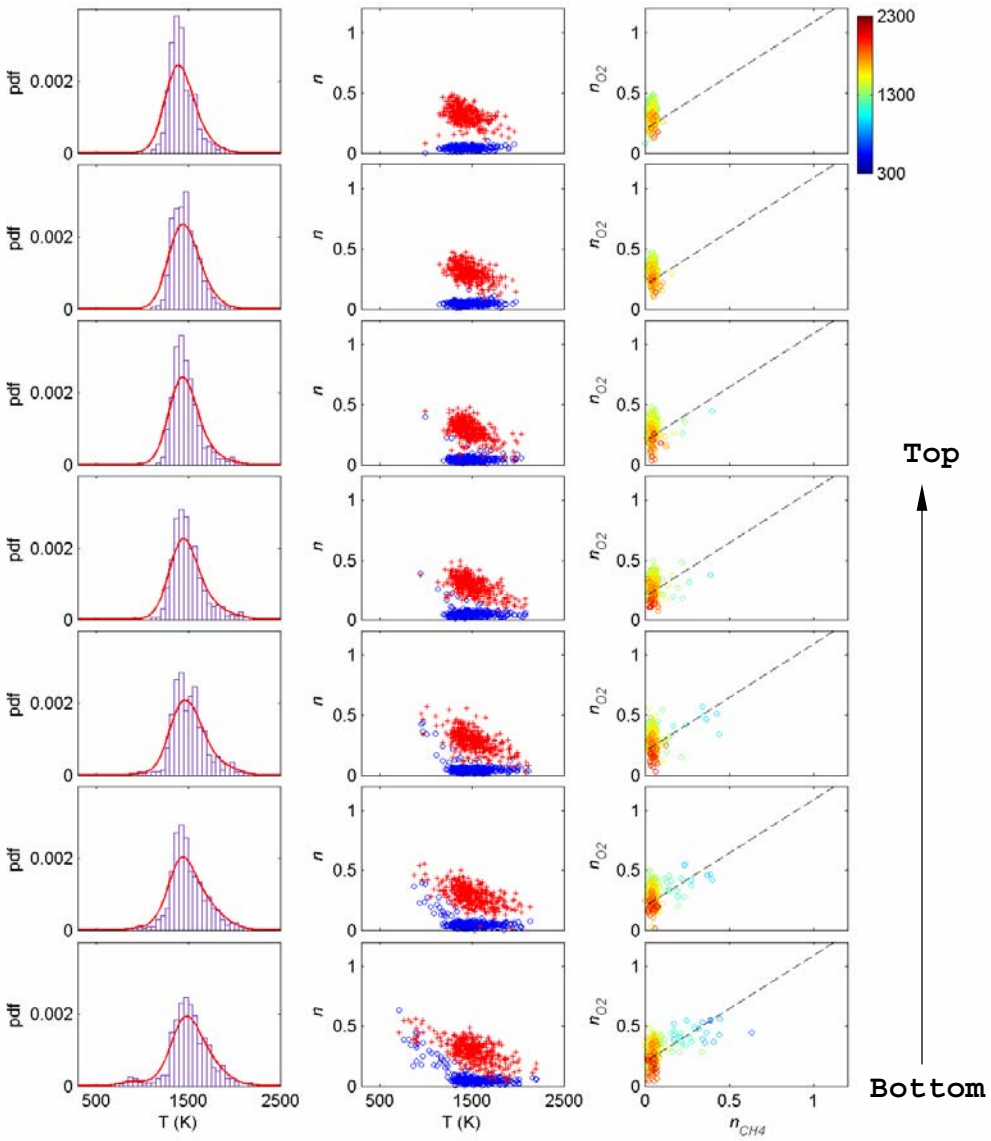
✓ Unique bi-modal PDF's — recirculation zone, or combustion oscillations

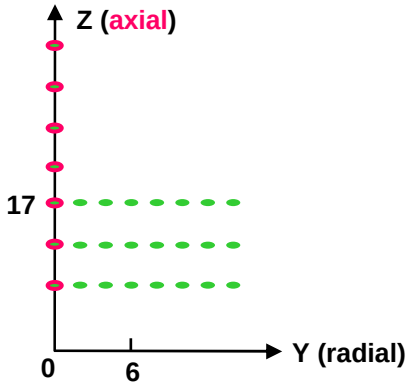
✓ Turbulent-chemistry interaction

✓ Fuel-air mixing characteristics

✓ Unburnt pockets

Multiscalar Analysis in 5-atm CH_4-Air LDI Flame





Data interpretation

- ✓ Gaussian-like narrow Temp. distribution (centered around the adiabatic temp. at Phi of 0.5)
- ✓ No fuel (CH_4) residual = fully consumed
- ✓ No hot or cold spots

✓ Homogeneous, well-reacted post-flame zone

Conclusions

- A single-shot (time-resolve) capability of a laser Raman diagnostics has been confirmed.
- Preliminary data of time-resolved multiscalar data in a high-pressure (turbulent) swirl-stabilized flame has been acquired.
- A new single-shot data-processing scheme (computer code) has been developed for ‘production mode’ thermo-chemical analysis.
- Scalar PDF’s and 3D (temp-oxy-fuel) correlations showed promising capability of future use in code validation

Work-in-progress

- APCD (atmospheric pressure combustion diagnostics) facility is under construction to calibrate and improve the Raman diagnostics applicable to liquid fuels
- Modified visible and UV Raman diagnostic systems is under development to cope with harsh environments
- Computer code to simulate Raman spectra of major species including CO_2 and H_2O (except hydrocarbon) is under development to complete the calibration matrix
- Pressure Safety Office safety permits, variances in process.